On Context-Aware Communication Mode Selection in Hybrid Vehicular Networks

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***Abstract*—Future vehicles will most-likely have multiple communication technologies and modes available. After classifying V2X applications in five distinct classes, a context-aware selection of the communication mode is advocated. A suitable architecture is outlined. First simulation results for the example of a DENM-based application indicate that a context-aware selection outperforms a static assignment.**

***Index Terms*—hybrid vehicular networks, requirements, context-indicators.**

I. Introduction

Vehicle-to-vehicle and vehicle-to-infrastructure communication, often summarized as vehicle-to-X (V2X) communication, has been an active research topic for more than a decade. Respective standards have been defined, e.g. in Europe with the ITS-G5 or the US with the WAVE/IEEE 1609 standards. However, until now no OEM has introduced V2X-communication based on these WLAN-like technologies on a larger scale. On the other hand, cellular communication technologies – for voice and data communication – are standard in medium and high end vehicles. Cellular data communication is used to connect to a (OEM-specific) backend system, e.g. in order to perform infotainment functionalities such as online search or to obtain online traffic information.

More recently, the standardization bodies for cellular communications have added variants of direct communication, e.g. the so-called proximity services allow Device-to-Device (D2D) communication as part of the LTE standards. While these extensions where not initially developed for vehicular applications, it is now considered in a recent 3GPP study [1]. Furthermore, the automotive industry is considered an important application sector for the future 5G cellular standards [2], which will most-likely also support a direct communication. The motivation to include direct communication in cellular standards for vehicular use-cases is two-fold: Some vehicular use-case require high message rates (in the order of 10 Hz or more) and low delays which are hard to achieve by indirect cellular communication and would most-likely require a high level of spacial reuse, i.e. high cost of deployment. Additionally, from the mobile operator point of view, direct communication can reduce the traffic (and resulting costs) in the core network, a fact that is also exploited by offloading [3] in other domains.

Therefore, it can be assumed that future connected vehicles will have multiple communication modes available: cellular/indirect communication and direct communication, the latter either provided by the well-known IEEE 802.11p or as part of the cellular standard itself. Depending on the coverage situation of the vehicle, four different situations can be distinguished, as illustrated in Fig. 1. This implies that depending on the local situation of a vehicle, the communication mode must be selected depending on criteria such as QoS requirements of an application (i.e. latency requirements, dissemination area, etc.), status of each communication mode (availability, current load, signal strength, etc.), number of other vehicles in range, and many more.

This context-aware selection of the suitable communication mode is particularly important during the phase of market introduction of the direct communication technology: During the first years of market introduction of the direct communication technology in most situations there will be no communication partner in range for direct communication. However, since cellular communication can rely on an existing, already deployed infrastructure, a vehicle aware of this situation can switch to cellular communication. In contrast, when a high market penetration has been achieved, vehicles should detect situations with highly loaded cellular networks and/or multiple vehicle with direct communication capabilities within range, in order to reduce the load in the core network of the cellular system and to avoid overload conditions.

The process of selecting the appropriate communication mode is non-trivial and – in order to avoid redundant, potentially inconsistent, implementation – from our point of

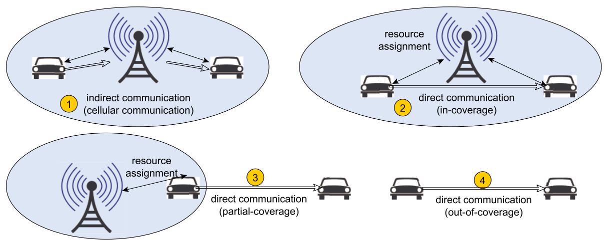

Fig. 1. Communication modes for cellular and direct communication.

view should be implemented in an intermediate communication layer, transparently handling the selection process from the application. The paper first presents a classification of vehicular networking applications along with their requirements. Four diverse use-cases, representative of each class and the applicability of the various wireless technologies, are discussed further. Based on these observations, a novel Hybrid Overlay Protocol (HOP) layer is proposed, which uses context-indicators in order to select the optimal communication mode. The paper concludes with preliminary simulation results for a specific context indicator, the number of vehicles in direct communication range, which illustrate the benefits of the proposed concept.

A. Related Work

In general, the challenge of selecting the appropriate communication mode in cellular networks supporting direct/D2D communication has been considered in several publications, an overview is given in [4]. Criteria such as the distance or the link quality to a direct communication partner are considered. However, these criteria are difficult to apply in C2X communication due to the rapidly changing positions and link qualities. For hybrid vehicular networks, Zheng et. al. in [5] introduce a Hybrid Link Layer (HLL) for load and resource sharing between cellular networks and IEEE 802.11p. In contrast, the focus of our work is not load sharing but selecting the optimal mode and technology on a per-packet basis according to the requirements/class of the generating application.

II. Vehicular Networking Applications – Requirements and Challenges

V2X applications are usually classified into safety and non-safety based categories. Within this article, a more specific classification of applications into five classes is put forward based on specific requirements on the wireless technologies:

Cooperative Sensing (Safety) applications use V2X communication for situation awareness, e.g. to reduce risks of accidents while driving. Vehicles in a local area communicate periodically in order to inform each other about their position, speed, acceleration and path, for example via periodic Cooperative Awareness Messages (CAM). The challenge here is finding low-latency, reliable, and efficient methods for disseminating safety-relevant data among neighbouring vehicles.

Cooperative Sensing (Information/Non-Safety) applications use communication to extend the horizon of perception for driver information systems. While conventional on-board sensors of a vehicle (e.g. camera, radar or lidar) depend on a line-of-sight situation and are limited to a range of approx. 50-200 meters, V2X communication can overcome these limits. The delay and reliability requirements are not as stringent as for safety applications, but the range in which the vehicle needs to be aware of relevant information is large, i.e. in general it exceeds 5 km.

Cooperative Maneuvering applications apply C2X communication for driving automation functions in the levels 3 to 5 as defined in SAE J3016. In order to realize cooperative maneuvers, vehicles use bidirectional communication, e.g. in order to exchange information on planned trajectories and agree on trajectory changes. Low latency ($\leq$ 10ms, [2]), reliable bi-directional communication is a key requirement for this application class.

In-Vehicle Internet Access applications extend the Internet into the vehicle by offering Internet-based applications for the driver and passengers. The acceptable delay as well as the required data rate are similar to those of typical smartphone use-cases.

Mobility Monitoring and Configuration applications involve communicating with a (usually parked) vehicle remotely in order to obtain information on its status. The user interacts with the vehicle via smartphone or using an Internet website.

A. Applicability of Wireless Technologies

The use-case classes in Sec. II differ to a large extent in their requirements and applicable technologies (Tab. I[1]). For safety applications, the stringent low delay requirements cannot always be fulfilled by current cellular technologies. 5G technologies might include a low-latency direct communication mode, e. g. as evaluated in the METIS project. Cooperative Sensing (Non-safety) applications involve a larger area of dissemination and interaction with fewer vehicles which can often be satisfied by cellular communications and by direct communication – if a suitable data dissemination scheme is applied [6].

III. Hybrid Overlay Protocol (HOP)

As motivated in Sec. I, the proposed solution to match the widely varying requirements of the application classes of Sec. II to the capabilities of the wireless communication technologies and modes in a specific context is to introduce an intermediate HOP layer, as illustrated in Fig. 2. This basic idea has already been introduced in a previous article [7], whereas the focus in this article is on the context-aware communication mode selection. Therefore, we will summarize the main aspects relevant for the presented results.

A. Basic Concept

Future V2X communication systems will support communication in at least two modes: a direct/ad-hoc mode and a indirect/cellular mode. Considering the highly dynamic vehicular environment with rapidly changing transmission conditions, the HOP layer adaptively decides the optimal communication mode on a per-packet basis. The selection of the communication mode involves the calculation of values characterizing the current context of the vehicle, termed Context Indicators (CIs) in the following. CIs can be based on vehicle sensors, e.g. vehicle speed, or on (meta-)information received from the

[1]Technologies that cannot completely fulfil all requirements are enclosed in parentheses. For 5G, a suitable direct communication mode is assumed.

TABLE I
APPLICABILITY OF WIRELESS TECHNOLOGIES

Category	Use Case Example	Applicable Wireless Technologies
Cooperative Sensing (Safety)	Intersection Collision Avoidance	802.11p, 5G, (UMTS, LTE, LTE-A)
Cooperative Sensing (Non-safety)	Dynamic Map Information	(802.11p, LTE-A D2D), UMTS, LTE, LTE-A, 5G
Cooperative Maneuvering	Cooperative Lane-Merging	(802.11p, LTE-A), 5G
In-Vehicle Internet Access	Information Retrieval from Internet Websites	UMTS, LTE, LTE-A, 5G
Mobility Monitoring and Configuration	Car Status Information	GPRS/EDGE, UMTS, LTE, LTE-A, 5G

lower communication layers, e.g. average data rate, channel busy time ratio, etc. In addition to the data payload, the applications also specify their requirements in form of requirement indicators (RIs) such as the maximum latency, range of dissemination, etc. The communication mode is then selected by matching the calculated CI's with the target RI's.

1) Context-Aware Communication Mode Selection: For initial simulations, three CIs are considered:

Channel Quality Indicator (CQI) of the LTE downlink. Cellular mode is used only when the CQI value measured is above a threshold value C_{CQI}.

Queue length of LTE in uplink. If it exceeds C_{LTEqueue}, the cellular network is assumed to be highly loaded.

1- & 2-hop Neighbour Count of vehicles capable of direct communication seen in the last T_{neigh} seconds. If the number of vehicles in 2-hop range exceeds C_{2hop}, it is assumed that information can be disseminated in a large area via direct mode.

2) Mode Selection: is performed based on these three CQIs in the following way: In case of poor conditions for cellular networks are indicated (CQI $\leq C_{\mathrm{CQI}}$ or queue length $> C_{\mathrm{LTEqueue}}$), direct mode is selected. In case of good cellular conditions, cellular mode is selected if less than C_{2hop} neighbours are in two-hop range, or if the cellular network has not been used for a period of T_{cell}. In all other cases, direct mode is selected. The rationale for the latter is to guarantee a minimum rate of messages on the cellular network, to reduce the delay for wide-area dissemination of messages (assuming the RI indicates a large dissemination range). The CQI and neighbour count values are periodically updated at a configurable frequency independent of the mode selection, queue length CI is updated via signal from MAC to HOP layer.

B. Simulation

For simulative evaluation, the proposed architecture is implemented in the discrete event simulator OMNeT++ 5.0b3. The network simulation is based on the INET-framework in version 3.2.1, SimuLTE [8] for simulating the LTE user plane and veins/veinslte [9]. As a first step, an example application of the Cooperative Sensing (Information/Non-Safety) class is investigated which sends Decentralized Environmental Notification Messages (DENMs). Received DENMs are forwared using Contention-Based Forwarding (CBF) and repeated for a duration of 5 mins. Performance criteria is the number of DENMs with unique actionIDs received *on time to react*. A message is received on-time if its delay is less than the time needed by a fast vehicle (180 km/h) to get to the position where it was sent, i.e. a driver has sufficient time to react.

Due to the limited space, we present only a single 2x2 highway scenario with a traffic density of 8.33 veh/lane/km where 5% of the vehicles use C2X communication. Vehicles generate DENMs with new ActionIDs with normally-distributed inter-event times with a mean of 30 s and a standard deviation of 10s. A single LTE cell using 100 RBs in a ITU-T rural macro-cell scenario is used for cellular communication, for direct communication IEEE 802.11p (with veins default parameter values) is used. Context-aware communication mode selection is based on the CIs described in Sec. III-A1 with parameters $C_{\mathrm{CQI}} = 0$, $C_{\mathrm{LTEqueue}} = 20kB$ and $C_{\mathrm{2hop}} = 10$.

Fig. 3 compares the proposed CI-based scheme with IEEE 802.11p only, LTE-A only. In order to obtain an upper-bound for the performance, we also show the result if all messages are always sent on both media and the one, which is received earliest, is counted. It can be observed that for lower distances, direct communication outperforms cellular communication. For larger distances, LTE outperforms direct communication, as it can be expected in this kind of scenario. The adaptive scheme outperforms both single technologies. However, for medium distances, redundant transmission on both media is outperforming the adaptive scheme – indicating that the adaptive selection is non-optimal in some cases.

C. Conclusions

Following a classification of V2X use-cases in five distinct categories, in this article, a hybrid overlay architecture has been advocated which performs a context-aware selection of communication modes in case multiple modes are available. Initial simulation results for a mode selection scheme based on CQI, cellular queue length and number of neighbors illustrate that an adaptive selection can outperform a static selection. A systematic investigation of CIs and their performance is therefore the next step.

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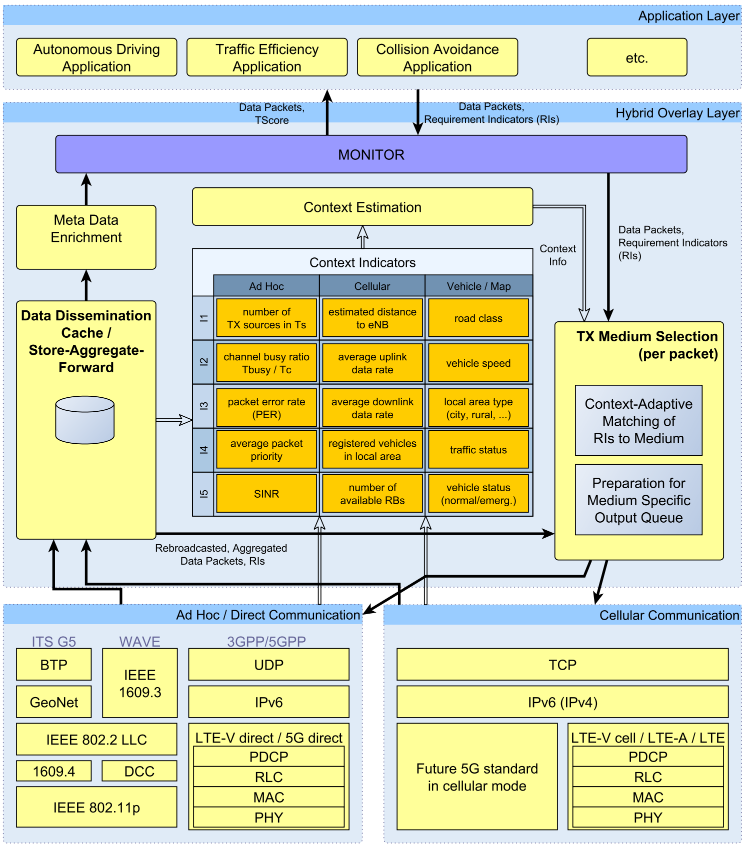

Fig. 2. Architecture of Hybrid Overlay Protocol (HOP) Layer and its proposed integration in the communication stack. Solid lines indicate the flow of the data packets, contoured lines indicate the flow of status/meta-information.

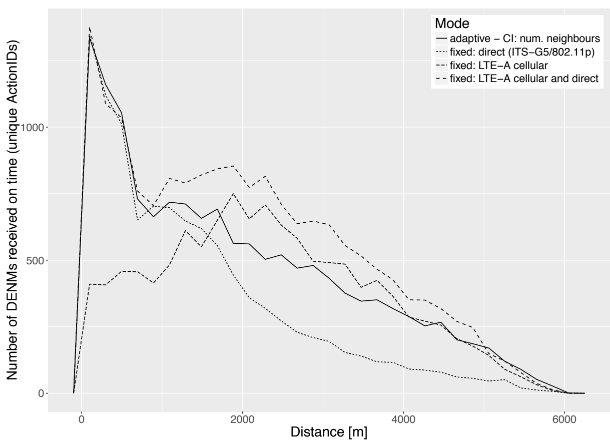

Fig. 3. Comparison of number of DENMs (uniq. action-ID) received on time.

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